Catalytic Transfer Hydrogenation

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I. Introduction

The reduction of multiple bonds using hydrogen gas and a metal catalyst is a reaction familiar to all organic chemists. Far less well known is the possibility of achieving reduction with the aid of an organic molecule as the hydrogen donor in the presence of a catalyst, a process known as *catalytic transfer hydrogenation*. This process is but one of several possible hydrogen transfer reactions which were classified by Braude and Linstead[1] as:

a. Hydrogen migrations, taking place within one molecule
b. Hydrogen disproportionation, transfer between identical donor and acceptor units
c. Transfer hydrogenation–dehydrogenation, occurring between unlike donor and acceptor units

Each of these reaction types in turn can be realized in principle by thermal means, homogeneous catalysis, heterogeneous catalysis, photochemical means, or with biological processes.

This review will concern itself with type c reactions, together with homogeneous or heterogeneous catalysis. Only the use of organic hydrogen donors will be discussed, although inorganic donors also fulfill this role. The use of hydrazine in such reactions has been reviewed recently.[2]

In 1952, Braude, Linstead, *et al.*,[3] made the suggestion that catalytic hydrogen transfer from an organic donor molecule to a variety of organic acceptors might be possible under mild conditions. In fact, sporadic use had been made in the past of unsaturated compounds as hydrogen acceptors in catalytic dehydrogenation reactions. However, few systematic studies were directed toward the reverse process, catalytic transfer hydrogenation.

Knowledge of the basic reaction, however, goes back to the turn of the century, when Knoevenagel[4] first observed that dimethyl 1,4-dihydroterephthalate disproportionated readily in the presence of palladium black to dimethyl terephthalate and (mostly *cis*) hexahydroterephthalate. Several years later, Wieland[5] observed the same reaction with dihydronaphthalene. Wieland predicted that the reaction would also occur with the then unknown dihydrobenzenes, a prediction confirmed by the work of Zelinski and Pavlov[6] and Corson and Ipatieff[7] in the 1930's. In the next decade attention was focused principally on catalytic dehydrogenation, especially through the systematic efforts of Linstead and his students. The important reaction variables were determined, the preparations of catalysts systematized, and the applications broadened. In 1952, Braude, Linstead, *et al.*,[3] reported the striking discovery that ethylenic and acetylenic linkages could be reduced in high yield and purity by refluxing with cyclohexene in tetrahydrofuran at 65° in the presence of palladium black. Subsequent studies established the scope of the reaction. It was shown that, in addition to reduction of ethylenic and acetylenic linkages, aliphatic and aromatic nitro groups could be reduced to primary amines. Azo, azoxy, and azomethine groups undergo reduction as well; halides can be hydrogenolyzed. It was further shown that carbonyl groups are generally not susceptible to reduction unless part of a potential aromatic system, as is the case with quinones or decalones. Nitriles were initially reported as unreactive, but later studies by Kindler and Lührs[8] provided the conditions for their reduction as well.

More recent work has brought the use of homogeneous catalysts with this reaction.[9-13] Investigations have continued on the synthetic applications of the reaction, as well as molecular details in the donor and acceptor structures, the effect of various catalysts, and the use of different solvents.[14]

Other investigations related in a general way to the topic under consideration are studies on the disproportionation of various hydroaromatic molecules[15-18] and the use of simple organic acceptors such as maleic acid and acetone for the aromatization of alkaloids, heterocyclics, and steroids.[19-22] These will not be discussed in any detail.

This review will present what is known about the major reaction variables, the scope of the reaction, and the

TABLE I. Hydrogen Donor Compounds

Compound	Catalyst	Ref
Cyclohexene	Pd	27–34, 36, 37, 42, 48
Subst cyclohexenes	Pd	3, 26, 34, 48
1,3-Cyclohexadiene	Pd	3, 42
1,4-Cyclohexadiene	Pd	3
trans-Δ^2-Octalin	Pd	15
$\Delta^{9,10}$-Octalin	Pd	15
1-Methyloctalin	Pd	15
trans-2-Methyloctalin	Pd	15
Tetralin	Pd	14, 24, 35, 39, 42, 43, 58
1,6-Dimethyltetralin	Pd	24
6-Methyltetralin	Pd	24
d-Limonene	Pd	14, 16, 30
α-Pinene	Pd	14, 31
β-Pinene	Pd	14, 31
Δ^3-Carene	Pd	47
α-Phellandrene	Pd	14, 31, 38, 44
β-Phellandrene	Pd	31
Terpinolene	Pd	14, 31
Δ^1-*p*-Menthene	Pd	8, 14, 45, 46
Cadalene	Pd	16
Pulegone	Pd	16
Selinene	Pd	16
Ethanol	Raney nickel	40
2-Propanol	Raney nickel	40
	$HIrCl_2(Me_2SO)_3$	10, 11
Methanol	$PtCl_2(Ph_3As)_2 + SnCl_2 \cdot H_2O$	9
Diethylcarbinol	Raney nickel	40
Octanol	$RuCl_2(Ph_3P)_3$	12
Cyclohexanol	Raney nickel	40
Benzyl alcohol	$RuCl_2(Ph_3P)_3$	12
β-Phenylethanol	$RuCl_2(Ph_3P)_3$	12
α-Phenylethanol	$RuCl_2(Ph_3P)_3$	12
o-Cyclohexylphenol	Pd	41
Formic acid	$RhCl(Ph_3P)_3$, $RuCl_2(Ph_3P)_3$, $IrBr(CO)(Ph_3P)_2$	13

mechanistic proposals for catalytic transfer hydrogenation.

II. Reaction Conditions

A. Nature of the Donor

The reaction under discussion can be generalized as in eq 1. The donor compound DH_x can, in principle, be any

$$DH_x + nA \xrightarrow[\text{solvent}]{\text{catalyst}} nAH_x + D \quad (1)$$

organic compound whose oxidation potential is sufficiently low so that the hydrogen transfer can occur under mild conditions. At higher temperatures, especially in the presence of catalysts, almost any organic compound can donate hydrogen (catalytic cracking), but this has little potential for controlled synthesis. Similarly, at sufficiently high temperatures (>300°) even benzene can serve as acceptor A and be reduced to cyclohexane.[23] Therefore the choice of donor is generally determined by the ease of reaction and availability. The chosen compounds tend to be hydroaromatics, unsaturated terpenes, and alcohols. Table I lists most of the donors which have been reported.

Cyclohexene, because of its ready availability and high reactivity, is the preferred hydrogen donor. However, frequently the temperature available with cyclohexene is not sufficient to cause reduction at an adequate rate. Therefore, tetralin or the readily available monoterpenes limonene, terpinolene, or α-phellandrene are also frequently used. In general, however, it may be said that any hydroaromatic compound capable of disproportionation can be utilized.[25] The specific choice depends as well on the nature of the functional group to be reduced. Thus the reduction of carbonyl groups requires the use of alcohols as donors.[40]

TABLE II.[14] Reduction of Cinnamic Acid in the Presence of Various Donors[a]

Donor	Solvent (xylene)	Reaction time[b]
p-Menthane	Absent	16 hr (only trace redn)
Δ^1-*p*-Menthene	Present	100 min
α-Phellandrene	Present	2 min
Limonene	Present	3 min
α-Pinene	Absent	300 min
β-Pinene	Absent	360 min
Camphene	Absent	360 min (no reaction)
Tetralin	Present	60 min
Decalin	Absent	360 min (only trace redn)

[a] Reaction conditions: catalyst 10% Pd/C; temp with xylene as solvent approximately 144° at reflux; otherwise reflux temp of donor. [b] Reaction time refers to quantitative conversion to hydrocinnamic acid, unless otherwise noted.

TABLE III.[14] Donor Activity with Various Acceptors[a]

Donor	Acceptors[b] A	B	C	D
α-Phellandrene	2 min[c]	1	2	8
d-Limonene	3	15	3	12
p-Menthene	100	30	25	40
α-Pinene				3600
Tetralin	60	20		

[a] Reaction conditions: 2.5 mmol of acceptor; 5.0 g of donor; 0.2 g of 10% Pd/C; 20 cc of xylene, reflux. [b] A = cinnamic acid; B = 3,4-methylenedioxycinnamic acid; C = *p*-methoxycinnamic acid; D = oleic acid. [c] Time to quantitative conversion.

Aside from obvious reaction limitations such as solubility, there are important differences in the reaction rates. This is illustrated in Table II. Here the times required for the quantitative reduction of cinnamic acid with various donors are compared.

It can be seen that, in the case of the various terpene donors, increasing unsaturation leads to more rapid reaction. Thus dienes are more reactive than enes, while saturated ring systems react slowly or not at all. However, a note of caution is appropriate here. A careful study of the reduction of mesityl oxide with *d*-limonene has shown that it is not limonene but rather Δ^1-*p*-menthene, formed as an intermediate by disproportionation, which actually serves as the donor species.[30] A complex mixture of intermediates also occurs during disproportionation of α-pinene.[47] Especially notable, from a practical point of view, is the short reaction time with the more reactive donors limonene and α-phellandrene. Similar trends are shown with a somewhat wider range of acceptors (Table III).

The slow reaction of the pinenes is, of course, not surprising since they cannot aromatize until the four-membered ring is cleaved. It seems likely that it is not pinene itself but a reaction intermediate which serves as actual hydrogen donor, as with limonene. The high reactivity of phellandrene and limonene is shown with a variety of other acceptors.

A more detailed study of the relationship of donor structure to reactivity has been reported by French workers.[26,34] Their results are shown in Table IV. The increas-

TABLE IV.[26,34] Effect of Substitution in Cyclohexene on Donor Activity[a]

R	% succinic acid after 48 hr	% hydrocinnamic acid after 72 hr	% *p*-toluidine
H	96.3	100	95
CH_3	75	50	
CH_3CH_2	34	15	4.85
$(CH_3)_2CH$	24	4	0
$CH_3(CH_2)_3$	24.5	2.5	2.13
Cyclohexyl	10	Trace	2.19
Phenyl	50	34.5	9.35

[a] Reaction conditions: 0.01 mol of maleic or cinnamic acid; 0.02 mol of donor; 50 mg of 5% Pd/C; 25 ml of THF, reflux; 0.0167 mol of *p*-nitrotoluene; 0.05 mol of donor; 100 mg of 5% Pd/C; 82°.

ing bulk of the substituent clearly reduces the rate of reaction, whereas activating substituents such as phenyl increase the rate again. The interesting question is raised here whether this effect is due to participation of the donor in the hydrogen transfer step or whether the difference simply reflects the relative ease of dehydrogenation of the various cyclohexenes. That the former is more likely may be inferred from the fact that after 48 hr under the same conditions, but without an acceptor, cyclohexene, 1-ethylcyclohexene, and 1-phenylcyclohexene are essentially completely dehydrogenated.[34]

B. Effect of Solvents

The effect of solvents on the course of the reaction has been studied in a limited number of cases. These results are presented in Table V. Greater sensitivity to the nature of the solvent is shown in the reduction of nitro compounds. This is shown in Table VI. The special effectiveness of tetrahydrofuran was noted by Gaiffe and Plotiau,[31] but the results of Braude, *et al.*,[48] suggest that such large differences between solvents do not exist. Use of a more effective donor such as α-phellandrene raises the yields of *p*-toluidine to 95%.[26]

The effect of solvent on the system cinnamic acid acceptor–α-phellandrene donor was also studied.[14] The following general conclusions seem warranted. Below a critical temperature, dependent on the donor (*ca.* 90° for limonene), little or no hydrogen transfer occurs. Above this threshold temperature, the reaction rate increases rapidly and appears to be independent of the nature of the solvent as far as hydrocarbons, acids, or ethers are involved. Alcohols and amines, which have the capability of reacting themselves with the catalyst (see below), appear to retard the reaction somewhat.

When using alcohols as solvents, it must be considered that these can also serve as hydrogen donors, especially when Raney nickel is used as catalyst.[40] It is therefore possible that hydrogen transfer takes place from solvent to donor, thereby reducing the reaction rate. Amines are also dehydrogenated by Raney nickel,[49-51] and a similar problem may occur.

The possibility of a competitive inhibition by certain functional groups seems to have been observed early by Kindler and Peschke.[44] They noted that *p*-nitrocinnamic acid was not reduced by α-phellandrene under conditions which readily reduced *p*-methoxycinnamic acid. A certain amount of free hydrogen gas is nevertheless evolved during the reaction. When *p*-nitrocinnamic acid and *p*-methoxycinnamic acid were combined, the methoxy compound was not reduced, and the evolution of free hydrogen greatly decreased. Similarly, Braude, *et al.*, noted the inhibitory effect of an aldehyde group in the reduction of nitrobenzaldehydes.[48] These functional groups would therefore be disadvantageous in a solvent. Within these limits, a wide range of solvents, including carboxylic acids, can be used.

TABLE V.[14] Effect of Solvent on Transfer Hydrogenation of *p*-Methoxycinnamic Acid[a]

Solvent	Bp, °C	Reaction time, min
p-Cymene	175	1
p-Menthane	170	1
Mesitylene	165	3
Xylene	140	10
Toluene	111	90
Toluene + benzene	102	330
Toluene + benzene	90	2760
Isovaleric acid	176	1
Isobutyric acid	154	1
Acetic acid	118	20
p-Methylanisole	177	1
Phenyl methyl ether	154	5
Hexanol	156	10
N,N-Dimethylaniline	193	10
N,N-Dimethylcyclohexylamine	162	20

[a] Reaction conditions: 0.0025 mol of *p*-methoxycinnamic acid; 0.0368 mol of *d*-limonene; 0.4 g 5% Pd/C; 20 ml of solvent refluxed until quantitative reduction occurred.

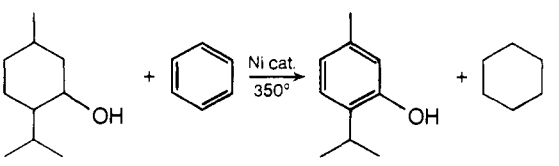
TABLE VI.[31,48] Effect of Solvent on Transfer Hydrogenation of *p*-Nitrotoluene

Solvent	Bp, °C	Yield of *p*-toluidine, % [a]	[b]
Xylene	120	49.8	
Toluene	105	20.75	
Benzene	104	28.25	73[c] (16)
Cyclohexane	85	4.7	75
Acetic acid	118		55
Acetone	60	4.15	90
Tetrahydrofuran	70	55.6	85
Diethyl ether	39	0	55
Methanol	56	0	
Ethanol	80	9.6	77

[a] Reaction conditions: 0.05 mol of cyclohexene donor; 0.067 mol of *p*-nitrotoluene acceptor; 100 mg of 5% Pd/C; 50 ml of solvent, refluxed 24 hr. [b] Reaction conditions: 0.056 mol of cyclohexene donor; 0.0182 mol of *p*-nitrotoluene acceptor; 20 mg of Pd black; 50 ml of solvent refluxed 17 hr. [c] The higher yield is obtained with benzene purified by refluxing with Raney nickel and distillation.

C. Effect of Temperature

As was noted above, temperature appears to be a very critical variable for catalytic transfer hydrogenation. Indeed at higher temperatures, in the range 300–350°, hydrogen transfers can be used to hydrogenate benzene to cyclohexane as mentioned earlier.[23] Generally such reactions have been used for aromatization, however, rather than to effect hydrogenation. An example of such a reaction is shown below in eq 2.



(2)

TABLE VII. Catalysts for Transfer Hydrogenation

Catalyst	Ref
Pd black	4, 5, 6, 32
Pd/C	8, 14–16, 19–22, 24–39, 42–46, 48
Pd/alumina	41
Ni/alumina	23
Ni/Kieselgur	7
Raney nickel	40, 49–51
$RuCl_2(Ph_3P)_3$	12, 13
$IrHCl_2(Me_2SO)_3$	10, 11
$IrBr(CO)(Ph_3P)_3$	13
$RhCl(Ph_3P)_3$	13
$PtCl_2(Ph_3As)_2 + SnCl_2 \cdot H_2O$	9

D. Effect of Catalyst

A number of different catalysts have been utilized for catalytic hydrogen transfer reactions. Some of the early discrepancies in these studies were undoubtedly due to subtle differences in catalyst preparation. The catalysts which have been reported are listed in Table VII. As may be gathered from the table, virtually all reported work has been done with palladium. Under standardized conditions when palladium is effective, neither platinum nor rhodium catalysts work, at least at temperatures below 200°. A more systematic study would be desirable, however, before this assertion is finalized.

Recently catalysts used for homogeneous hydrogenation have been used for transfer hydrogenation. These include the ruthenium complex $RuCl_2(Ph_3P)_3$,[12] the iridium complexes $HIrCl_2(Me_2SO)_3$,[10,11,13] $Ir(CO)Br(Ph_3P)_2$,[13] the rhodium complex $RhCl(Ph_3P)_3$,[13] and the platinum complex $PtCl_2(Ph_3As)_2 + SnCl_2 \cdot H_2O$.[9] In the latter case, it is not clear whether the tin or the platinum is the effective catalyst.

Raney nickel occupies a somewhat ambiguous place among the catalysts for transfer hydrogenation because of the demonstrated fact that the catalyst contains 40–110 ml/g of adsorbed hydrogen formed during generation of the catalyst.[52] Hence assertions that reduction with Raney nickel is due to hydrogen transfer from a donor have been questioned.[53] There is also evidence that some hydrogen is removed from hydroxylic solvents and Atkins, *et al.*, have shown that hydrogen transfer from alcohols to ethylene is possible with Raney nickel.[54] It is also clear that Raney nickel plays only a catalytic and not a donor role in the oxidation/hydrogen transfer of cholesterol to cholestenone.[40] Again further work is needed to determine if the catalyst-bound hydrogen, possibly nickel hydride, plays a major role in the quantitative reduction of multiple bonds, or whether it serves mainly to "activate" the catalyst.

For a comparison of the effectiveness of various catalysts, see the results presented by Braude, *et al.*,[48] in Table VIII. Clearly palladium catalysts are the most effective. With other donors, especially hydrazine, Pt/C and Raney nickel seem to work equally well.[2] It is interesting to note that nickel catalysts effect the disproportionation of cyclohexene under very mild conditions. Thus a nickel/kieselguhr catalyst converts cyclohexene quantitatively at 74° to benzene and cyclohexane in 15 sec.[7] Nonetheless the catalyst is ineffective in hydrogen transfer to an acceptor other than cyclohexene.

In another system, with limonene as donor and cinnamic acid as acceptor, platinum and rhodium catalysts were also found ineffective.[14]

The exceptional role of palladium in hydrogen transfer reactions appears to be due, at least in part, to its general mobilizing action for hydrogen–carbon bonds. For instance, palladium is much more effective than rhodium or platinum in causing rearrangements during regular catalytic hydrogenation of substituted cyclohexenes.[18]

TABLE VIII.[48] Comparison of Catalysts for Transfer Hydrogenation[a] of *p*-Nitrotoluene

Catalyst	Amount mg	Time, hr	Yield of *p*-toluidine, %
10% Pd/C	190	7	95
1% $Pd/CaCO_3$	100	18	95
0.1% Pd/Al_2O_3	1000	18	64
$PdCl_2$	20	17	1
Pd/Pt[b]	10	13	100
Pt black	20	7	18
10% Pt/C	350	7	13
PtO_2	45	17	0
Raney nickel	100	22	2
W 7 Raney nickel	100	100	2

[a] Reaction conditions: 2.5 g of *p*-nitrotoluene; 15 ml of cyclohexene; catalyst as per table; time reflux as per table. [b] Pd deposited electrolytically on platinum foil.

A great deal of emphasis was placed on the preparation of the catalyst in early work, but according to the recent literature, the commercially available catalysts are perfectly adequate.[14] Palladium is the catalyst of choice for most catalytic transfer hydrogenations.

E. Other Variables

As is frequently the case with heterogeneous reactions, mechanical agitation is very important. Linstead has shown that free ebullition is actually rate determining for the catalytic dehydrogenation of tetralols and tetralones to naphthols.[55] Here product distribution, *i.e.*, the ratio of naphthalenes to naphthols produced, was determined by temperature. As most catalytic transfer hydrogenations are carried out at reflux, this condition for optimum reaction is met. Nevertheless, the technique devised by Linstead of carrying out the reaction at lower temperatures by using a partial vacuum deserves consideration when greater selectivity is desired. Alternatively a solvent may be used.

III. Applicability

We have chosen to present typical applications of transfer hydrogenation with various functional groups and then to devote a special section to applications with a more general synthetic interest.

A. Reduction of Multiple Bonds

1. Olefins

A number of different olefins have been reduced by catalytic transfer hydrogenation. These are listed in Table IX which indicates that a considerable variety of olefinic compounds has been hydrogenated in good to excellent yields by transfer hydrogenation. Nitriles are usually completely reduced to methyl groups along with the double bond. Halogen is generally removed, including halide bound to an aromatic ring. This will be discussed further in section III.B.2.

2. Acetylenes

In contrast to the extensive work done with olefins, only very limited data are available for acetylenes, as shown in Table X. Nevertheless, it appears that it is possible to control the addition so that the intermediate *ene*

can be isolated in good yield as in conventional hydrogenation. Further, the stereochemical result is the familiar cis addition of hydrogen. As a matter of fact, in the case of the iridium complex $HIrCl_2(Me_2SO)_3$ a definite intermediate has been isolated (see section IV).[56]

3. Carbonyl Compounds

In general, carbonyl groups are not reduced with the commonly used catalyst Pd/C, although complete hydrogenolysis of α,β-unsaturated aldehydes in the steroid series has been reported.[29] However, Raney nickel does appear to catalyze hydrogen transfer from alcohols as shown in Table XI. With isolated exceptions, no generality can be claimed for the reduction of the carbonyl group. Raney nickel seems to be the most successful catalyst employed. The results achieved with a homogeneous iridium catalyst are not impressive. The partial reduction of *p*-quinone and benzil by the standard palladium system is not surprising since their reduction potentials are lower than those of ordinary carbonyl compounds.

Neither cyclopentanone nor heptanal could be reduced with cyclohexene, limonene, or *p*-menthene as donors and Pd/C, Pt/C, or Rh/C catalysts.[57]

4. Nitriles

Partial reduction of nitriles to imines has not been achieved by transfer hydrogenation, except with hydrazine as donor.[2] Generally nitriles are completely reduced to methyl groups under the conditions normally used for catalytic transfer hydrogenation. The reported examples are listed in Table XII.

In general then, according to the results in Table XII, the reduction of the cyano group bound to an aromatic or heterocyclic ring proceeds quite satisfactorily to the corresponding methyl group. On the other hand, aliphatic nitriles are reduced with more difficulty, and hydrogen gas must be added to achieve a measure of reduction. Trialkylamines are formed as side products by addition of intermediate alkylamines to intermediate imines[49,50] as shown in eq 3-6 (see also section III.B.1).

$$RCN \xrightarrow[Pd/C]{DH_2} RCH{=}NH \xrightarrow[Pd/C]{DH_2} RCH_2NH_2 \quad (3)$$

$$RCH_2NH_2 + RCH{=}NH \longrightarrow RCH(NHCH_2R){-}NH_2 \xrightarrow[DH_2]{Pd/C} RCH{=}NCH_2R + NH_3 \quad (4)$$

$$RCH{=}NCH_2R \xrightarrow[Pd/C]{DH_2} (RCH_2)_2NH \quad (5)$$

$$RCH{=}NH + (RCH_2)_2NH \longrightarrow RCH(N(CH_2R)_2){-}NH_2 \xrightarrow[DH_2]{Pd/C} (RCH_2)_3N + NH_3 \quad (6)$$

5. Imines, Hydroxylamines, Hydrazones

The few reported examples of a carbon–nitrogen double bond reduction are listed in Table XIII. Apparently only relatively stable systems were studied, and the general applicability is not clear. As in the case of the nitriles, the reaction does not stop at intermediate reduction stages, but proceeds directly to the corresponding alkane, as in conventional hydrogenolysis of benzylic amines.

6. Azo Compounds

Azobenzene has been converted to aniline in 97% yield using cyclohexene as donor and Pd/C as catalyst. 2,2′-Dimethoxyazobenzene gives 84% o-anisidine under the same conditions.[42] From azoxybenzene, again under the same conditions, one obtains only 8% aniline.

7. Nitro Compounds

Nitro compounds have been investigated rather extensively. The results are presented in Table XIV. From this table one can conclude that many commonly encountered functional groups are compatible with the reducing system. Thus nitro groups can be reduced in good yields to the corresponding amino compounds in the presence of keto, carboxyl, *N*-acetamido, nitrile, and phenolic hydroxyl groups. Aromatic aldehydes interfere with the reduction, probably by blocking the catalyst.[48] It is interesting to note the stability of the cyano group with cyclohexene as donor. As has been previously discussed, the nitrile group is reducible with the more active donor, *p*-menthene. Only one aliphatic case is reported, the reduction of nitropropane.

Certainly these catalytic transfer reductions at the very least are a considerable technical improvement over the rather messy traditional reduction with metals and acid. The catalytic transfer reactions appear to be more selective than regular catalytic hydrogenation.[48]

B. Hydrogenolysis

As has been pointed out in the previous section, hydrogenolysis frequently accompanies the reduction of multiple bonds. The more systematic studies of this reaction will now be discussed.

1. Nitriles

The carbon–nitrogen triple bond is generally reduced to a methyl group (see Tables IX and XII). There is, however, a definite indication of the intermediate formation of amines, which can react with intermediate imines to produce ultimately tertiary amines, according to eq 3-6. This reaction can be synthetically exploited for the production of nitrogen heterocycles as well as secondary amines. The details are given in section III.D.

2. Halides

Halogen in organic compounds is frequently removed under conditions of catalytic transfer hydrogenation. In addition to the instances cited in Tables IX and XII, the cases shown in Table XV have been reported.

From this table it is indicated that chlorine and bromine bound to an aromatic ring can be removed in good yield. One would assume that the same applies to iodine, although no examples were reported. Fluorine, on the other hand, is inert. An isolated example of the reduction of an acid chloride (benzoyl chloride) gave only a minimal yield of benzaldehyde.

3. Allylic and Benzylic Functional Groups

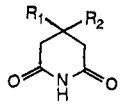
Because of the enhanced reactivity of allylic and benzylic compounds, it is to be expected that functional groups bound to these systems would hydrogenolyze rather easily as in conventional hydrogenation. This turns out to be the case with catalytic transfer hydrogenation as well. Table XVI gives examples of such reactions. Although the reported examples are not numerous, it is

TABLE IX. Catalytic Transfer Hydrogenation of Olefins

Acceptor	Catalyst[a]	Donor[b]	Product (yield, %)	Ref
		Hydrocarbons		
Heptene-1	2	B	*n*-Heptane (70)	32
Octene-1	1	A	*n*-Octane (70)	13
Octene-1	2	B	*n*-Octane (100)	13
Octene-2	1	A	*n*-Octane (75)	32
Octene-4	2	B	*n*-Octane (100)	13
Allylbenzene	1	A	*n*-Propylbenzene (90)	32
β-Methylstyrene	1	A	*n*-Propylbenzene (100)	32
α-Methylstyrene	3	C	Cumene (12)	10
Styrene	3	C	Ethylbenzene (16)	10
cis-Stilbene	1	A	Bibenzyl (100)	32
trans-Stilbene	1	A	Bibenzyl (100)	32
	3	C	Bibenzyl (1)	10
Stilbene	4	D	Bibenzyl (60)	40
1,1-Diphenylethylene	1	A	1,1-Diphenylethane (100)	32
	3	C	1,1-Diphenylethane (1)	10
Anthracene	5	E	1,2,3,4-Tetrahydroanthracene (61)	39
Acenaphthylene	1	A	Acenaphthene (100)	32
		Acids		
But-3-enoic acid	1	A	Butyric acid (90)	32
But-2-enoic acid	5	F	Butyric acid (100)	14
Crotonic acid	1	A	Butyric acid (89)	32
3-Methylbut-2-enoic acid	5	F	3-Methylbutyric acid (100)	14
Fumaric acid	5	F	Succinic acid (100)	14
Maleic acid	5	F	Succinic acid (100)	14
	1	A	Succinic acid (100)	32
Itaconic acid	3	C	Methylsuccinic acid (1)	10
Sorbic acid	1	A	Hexanoic acid (90)	32
	5	F	Hexanoic acid (100)	14
Muconic acid	1	A	Adipic acid (80)	32
Oleic acid	1	A	Stearic acid (40)	32
	5	F	Stearic acid (100)	14
Linoleic acid	5	F	Stearic acid (100)	14
β-Furylacrylic acid	5	E	β-Furylpropionic acid (92)	43
Cinnamic acid	1	A	Hydrocinnamic acid (90)[c]	32
	5	G	Hydrocinnamic acid (100)	14
	5	E	Hydrocinnamic acid (100)	43
p-Chlorocinnamic acid	5	E	*p*-Chlorohydrocinnamic acid (96)	43
	5	G	Hydrocinnamic acid (90)	14
p-Methoxycinnamic acid	5	F	*p*-Methoxyhydrocinnamic acid (100)	44
	5	G, H	*p*-Methoxyhydrocinnamic acid (*d*)	14
o-Methoxycinnamic acid	5	G	*o*-Methoxyhydrocinnamic acid (*d*)	14
p-Ethoxycinnamic acid	5	G	*p*-Ethoxyhydrocinnamic acid (*d*)	14
3,4-Dioxymethylenecinnamic acid	5	F	3,4-Dioxymethylenehydrocinnamic acid (100)	14
3-Methoxy-4-hydroxycinnamic acid	5	F	3-Methoxy-4-hydroxyhydrocinnamic acid (*d*)	14
p-Hydroxycinnamic acid	5	G	*p*-Hydroxyhydrocinnamic acid (*d*)	14
3,4-Dihydroxycinnamic acid	5	G	3,4-Dihydroxyhydrocinnamic acid (*d*)	14
p-Methylcinnamic acid	5	G	*p*-Methylhydrocinnamic acid (*d*)	14
α-Methylcinnamic acid	3	C	α-Methylhydrocinnamic acid (2)	10
α-Phenylcinnamic acid	5	G	α-Phenylhydrocinnamic acid (84)	57
p-$CH_3PhCH{=}C(Ph)COOH$	5	G	p-$CH_3PhCH_2CH(Ph)COOH$ (82)	57
$PhCH{=}C(NHCOCH_3)COOH$	5	G	$PhCH_2CH(NHCOCH_3)COOH$ (74)	57
$3,4\text{-}(CH_3O)_2PhCH{=}C(NHCOPh)_2COOH$	5	G	$3,4\text{-}(CH_3O)_2PhCH_2CH(NHCOPh)COOH$ (70–100)	14
$PhCH{=}CHCH{=}C(NHCOPh)COOH$	5	G	$PhCH_2CH_2CH_2CH(NHCOPh)COOH$ (*d*)	14
Piperic acid	5	G	3,4-Dioxymethylene$Ph(CH_2)_4COOH$ (*d*)	14
Atropic acid	3	C	Dihydroatropic acid (33)	10
		Ketones		
Cyclohexanone	3	C	Cyclohexanol (97)	10
Mesityl oxide	5	G	$(CH_3)_2CHCH_2COCH_3$ (90)	30
$PhCH{=}CHCOCH_3$	5	G	$PhCH_2CH_2COCH_3$ (70–100)	14
	6	I	$PhCH_2CH_2COOCH_3$ (94)	12
	6	E	$PhCH_2CH_2COCH_3$ (76)	12
$PhCH{=}CHCOPh$	6	I	$PhCH_2CH_2COPh$ (98)	12
	3	C	$PhCH_2CH_2COPh$ (95)	11
	5	G	$PhCH_2CH_2COPh$ (70–100)	14
$3,4\text{-}(CH_3CH_2O)PhCl{=}CHCOCH_3$	5	G	$3,4\text{-}(CH_3CH_2O)_2PhCH_2CH_2COCH_3$ (70–100)	14
p-$ClPhCH{=}CHCOPh$	5	F	$PhCH_2CH_2COPh$ (*d*)[c]	14

TABLE IX *(Continued)*

Acceptor	Catalyst[a]	Donor[b]	Product (yield, %)	Ref
p-$CH_3PhCH{=}CHCOPh$-p-OCH_3	4	D	p-$CH_3OPhCH_2CH_2COPh$-p-OCH_3 (80)	40
	5	G	p-$CH_3OPhCH_2CH_2COPh$-p-OCH_3 (70–100)	14
p-$CH_3OPhCH{=}CHCOPh$-3,4-$(CH_3CH_2O)_2$	5	F	p-$CH_3OPhCH_2CH_2COPh$-3,4-$(OCH_2CH_3)_2$ (70–100)	14
$PhCH{=}CHCOC(CH_3)_3$	6	I	$PhCH_2CH_2COC(CH_3)_3$ (89)	12
	3	C	$PhCH_2CH_2COC(CH_3)_3$ (90)	11
$PhCH{=}CHCH{=}CHCOPh$	5	F	$PhCH_2CH_2CH_2CH_2COPh$ (70–100)	14
	3	C	$PhCH_2CH_2CH_2CH_2COPh$ (90)	11
$PhCH{=}CHCH{=}CHCOPh$-p-OCH_3	5	F	$PhCH_2CH_2CH_2CH_2COPh$-p-OCH_3 (70–100)	14
$(PhCH{=}CH)_2CO$	3	C	$(PhCH_2CH_2)_2CO$ (65)	11
	5	F	$(PhCH_2)_2CO$ (*d*)	14
Isophorone	6	I	3,3,5-Trimethylcyclohexanone (41)	12
Pulegone	1	*e*	Menthone (51)	16
Cholestenone	4	*f*	Dihydrocholesterol (10)	40
17α-Acetoxy-6-methylenepregn-4-ene-3,20-dione	5	A	17α-Acetoxy-6α-methylpregn-4-ene-3,20-dione (?)	29
21-Acetoxy-6-methylenepregn-4-ene-3,20-dione	5	A	21-Acetoxy-6α-methylpregn-4-ene-3,20-dione (?)	29
			Aldehydes	
Crotonaldehyde	3	C	Butyraldehyde (40)	10
Cinnamaldehyde	3	C	$PhCH_2CH_2CHO$ (0–1)	10
$PhCH{=}C(CH_3)CHO$	6	I	$PhCH_2CH(CH_3)CHO$ (61)	12
17α-Acetoxy-6-formyl-3-methoxypregna-3,5-dien-20-one	5	A	17α-Acetoxy-6α-methylpregn-4-ene-3,20-dione (?)[c]	29
21-Acetoxy-6-formyl-3-methoxypregna-3,5-dien-20-one	5	A	21-Acetoxy-6α-methylpregn-4-ene-3,20-dione (?)[c]	29
21-Acetoxy-6-formyl-17-hydroxy-3-methoxypregna-3,5-diene-11,20-dione	5	A	6-α-Methylcortisone acetate (80)	29
			Esters	
$PhCH{=}CHCOOR$ ($R = C_2H_5$, C_4H_9, $C_6H_5CH_2$)	5	A, F	$PhCH_2CH_2COOR$ (100)	31
m-$ClPhCH{=}CHCOOCH_3$	5	G	$PhCH_2CH_2COOCH_3$ (90)[c]	14
Methyl linoleate	7	*g*	Monoene ester (51)	9
			Nitriles	
$PhCH{=}CPhCN$	5	H	$PhCH_2CHPhCH_3$ (70–80)[c]	8
3,4-$(CH_3O)_2PhCH{=}CHCN$	5	H	3,4-$Ph(CH_3O)_2PhCH_2CH_2CH_3$ (70–80)[c]	8
p-$CH_3OPhCH{=}C(p$-$CH_3Ph)CN$	5	H	p-$CH_3PhCH_2CH(p$-$CH_3Ph)CH_3$ (70–80)[c]	8
p-$CH_3PhCH{=}CPhCN$	5	H	p-$CH_3PhCH_2CHPhCH_3$ (70–80)[c]	8
3,4-MethylenedioxyPhCH=CPhCN	5	H	3,4-MethylenedioxyPh$CH_2CHPhCH_3$ (70–80)[c]	8
$PhCH{=}CHCH{=}CPhCN$	5	H	$PhCH_2CH_2CH_2CHPhCH_3$ (70–80)[c]	8
$PhCH{=}C(COOCH_2CH_3)CN$	5	H	$PhCH_2CH(COOCH_2CH_3)CH_3$ (81)[c]	45
$PhCH{=}C(COOCH(CH_3)_2)CN$	5	H	$PhCH_2CH(COOCH(CH_3)_2)CH_3$ (70)[c]	45
p-$CH_3PhCH{=}C(COOCH_2CH_3)CN$	5	H	p-$CH_3PhCH_2CH(COOCH_2CH_3)CH_3$ (63)[c]	45
3,4-$(CH_3O)_2PhCH{=}C(COOCH_2CH_3)CN$	5	H	3-4-$(CH_3)_2PhCH_2CH_2(COOCH_2CH_3)CH_3$ (0)	45
$Ph(CH_3)C{=}C(COOCH_2CH_3)CN$	5	H	$Ph(CH_3)CHCH(COOCH_2CH_3)CH_3$ (59)[c]	45
$Ph(CH_3CH_2)C{=}C(COOCH_2CH_3)CN$	5	H	$Ph(CH_3CH_2)CHCH(COOCH_2CH_3)CH_3$ (16)[c]	45
			Miscellaneous Compounds	
Maleic anhydride	5	F	Succinic anhydride (*d*)	14
Coumarin	5	G	Dihydrocoumarin (*d*)	14
Barbituric acids	5	F, G, H	Corresponding saturated barbituric acids (*d*)	14



R_1	R_2	R_1	R_2
allyl	allyl	allyl	isopropyl
allyl	phenyl	allyl	ethyl
1-cyclohexenyl	ethyl		

[a] Catalysts: 1, Pd black; 2, $RhCl_2(Ph_3P)$; 3, $IrCl_3(Me_2SO)_3$; 4, Raney nickel; 5, Pd/C; 6, $RuCl_2(Ph_3P)_3$; 7, $PtCl_2(Ph_3As)_2 + SnCl_2$. [b] Donors: A, cyclohexene; B, HCOOH/HCOOLi; C, isopropyl alcohol; D, diethylcarbinol; E, tetralin; F, α-phellandrene; G, limonene; H, Δ^1-p-menthene; I, $PhCH_2OH$. [c] Concurrent hydrogenolysis. [d] Specific yields not indicated, but approaching quantitative.[14] [e] Pulegone (disproport.). [f] Cyclohexanol. [g] Methanol.

clear that hydrogenolysis of allylic and benzylic functional groups can generally be expected. In addition it seems likely that a number of the reported reductions of carbonyl compounds to hydrocarbons (Table XI) proceed *via* intermediate benzylic alcohols. Certainly the nitriles reported in Table XII are reduced *via* a benzylic amines, insofar as such structures are possible.

4. *Amines*

A few examples have been reported of hydrogenolyses of amines in addition to the allylic and benzylic examples cited above. These include β-phenethylamine and di-β-phenethylamine, both of which are reduced to ethylbenzene in approximately 50% yield.[43] In general, however,

TABLE X. Catalytic Transfer Hydrogenation of Acetylenes

Acceptor	Catalyst	Donor	Product (yield, %)	Ref
Tolan	Pd black	Cyclohexene	*cis*-Stilbene (90)[a]	32
	Pd black	Cyclohexene	Bibenzyl (100)[b]	32
	Raney nickel	Ethanol	Bibenzyl (77)	40
	$HIrCl_2(Me_2SO)_3$	2-Propanol/H^+	*cis*-Stilbene (90)	56
Phenylacetylene	$HIrCl_2(Me_2SO)_3$	2-Propanol/H^+	Ethylbenzene (30)	10
Propynol	$HIrCl_2(Me_2SO)_3$	2-Propanol/H^+	1-Propanol (15)	10

[a] Reaction time, 3 hr. [b] Reaction time, 23 hr.

TABLE XI. Catalytic Transfer Hydrogenation of Carbonyl Compounds

Acceptor	Catalyst	Donor	Product (yield, %)	Ref
Benzophenone	Raney nickel	Diethylcarbinol	Diphenylmethane (75)[a]	40
	Raney nickel	2-Propanol	Diphenylmethane (36)[a]	40
Benzil	Pd/C	Cyclohexadiene	Benzoin (45)	42
Benzoin	Raney nickel	Cyclohexanol	Bibenzyl (58)[a]	40
Desoxybenzoin	Raney nickel	Cyclohexanol	Bibenzyl (20)[a]	40
Benzoquinone	Pd/C	Cyclohexadiene	Hydroquinone (70)	42
$(C_{11}H_{23})_2CO$	Raney nickel	2-Propanol	$(C_{11}H_{23})_2CHOH$ (80)	40
Ethyl *n*-benzoylbenzoate	Raney nickel	2-Propanol	*o*-Benzylbenzoic acid (86)[a,b]	40
3-Acetylquinoline	Raney nickel	2-Propanol	3-Ethyl-5,6,7,8-tetrahydroquinoline (62)[a]	40
p-CH_3OPhCH_2COPh-*p*-OCH_3	Raney nickel	Diethylcarbinol	*p,p'*-Dimethoxybibenzyl (80)[a]	40
p-$CH_3OPhCH{=}CHCOPh$-*p*-OCH_3	Raney nickel	Diethylcarbinol	*p*-$CH_3OPhCH_2CH_2CH_2Ph$-*p*-OCH_3 (80)[a]	40
Cholestanone	Raney nickel	Cyclohexanol	Dihydrocholesterol (50)	40
Coprostanone	Raney nickel	Cyclohexanol	Epicoprostanol (20)	40
Cholestenone	Raney nickel	Cyclohexanol	Dihydrocholesterol (10)	40
Butyraldehyde	$IrCl_3(Me_2SO)_3$	2-Propanol	Butanol (5)	10
p-Methoxybenzaldehyde	$IrCl_3(Me_2SO)_3$	2-Propanol	*p*-CH_3OPhCH_2OH (9)	10
9-Anthraldehyde	Raney nickel	2-Propanol	9-Hydroxymethylanthracene (10), anthracene (10)	40
17α-Acetoxy-6-formyl-3-methoxypregna-3,5-dien-20-one	Pd/C	Cyclohexene	17α-Acetoxy-6-methylpregn-3-ene-3,20-dione (?)[a]	29
21-Acetoxy-6-formyl-3-methoxypregna-3,5-dien-20-one	Pd/Cl	Cyclohexene	21-Acetoxy-6-methylpregn-3-ene-3,20-dione (?)[a]	29
21-Acetoxy-6-formyl-17-hydroxy-3-methoxypregna-3,5-diene-11,20-dione	Pd/Cl	Cyclohexene	21-Acetoxy-6-methyl-17-hydroxy-3-methoxypregna-3,5-diene-11,20-dione (?)[a]	29

[a] Concurrent hydrogenolysis. [b] After saponification.

the course of the reaction is more complex as indicated in section III.B.1.

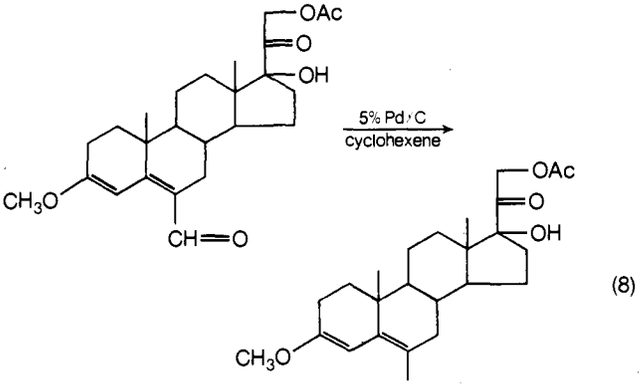
C. Structural Selectivity

The following general comments can be made regarding selectivity. Carbonyl groups are generally not attacked under the usual conditions with Pd/C. Therefore, ketones, acids, esters, and amides are not changed, as may be seen from Table XIV. Aldehyde groups are strongly adsorbed to the catalyst, and may therefore interfere with reduction, but are themselves not attacked.[48] Free amino groups also interfere, but this may be overcome by acetylation.[48] Ether groups are, as expected, inert. In α,β-unsaturated carbonyl compounds, only the double bond is reduced (Table IX). However, with α,β-unsaturated nitriles, both the double bond and the cyano group undergo reduction. It is not clear, however, in the latter case that an effort was made to determine conditions for a partial reduction of either the double bond or the cyano group. In any case, advantage was taken of differential reactivity in the reduction of benzylic esters (eq 7) which could be hydrogenolyzed in good yields

$$C_6H_5CHCN \quad \xrightarrow[\text{tetralin}]{\text{Pd/C}} \quad C_6H_5CH_2CN \ (ca.\ 70\%) \qquad (7)$$
$$\quad\quad |$$
$$\quad\quad OCOC_6H_5$$

without reducing the nitrile.[58] Nitro groups are also more easily reduced than nitriles (Table XIV).

More significant cases of selectivity were encountered in the steroid series. Here various steroid ethers of the general type represented in eq 8 were selectively reduced to 6-methyl steroids without affecting other functionalities.[29]



(8)

Again in the steroid series, selective reduction of an exocyclic double bond in preference to endocyclic saturation has been reported as in eq 9.[29]

An example of selectivity in the terpene series is the disproportionation of *d*-limonene to give Δ^1-*p*-menthene, a process which occurs rapidly before any appreciable transfer hydrogenation takes place (eq 10).

Another type of selectivity is found in the reduction of polynitrobenzenes. With transfer hydrogenation, only one

TABLE XII. Catalytic Transfer Hydrogenation of Nitriles (Pd/C Catalyst)[a]

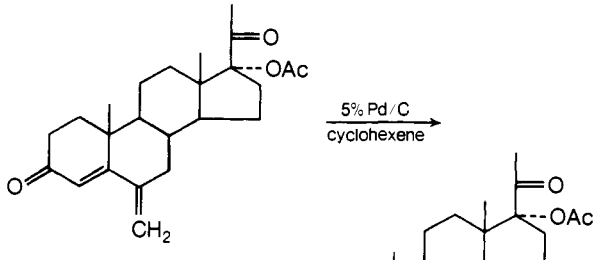
Acceptor	Donor	Product (yield, %)	Ref
Benzonitrile	*p*-Menthene	Toluene (85–90)	8
o-Chlorobenzonitrile	*p*-Menthene	Toluene (85–90)[b]	8
p-Chlorobenzonitrile	*p*-Menthene	Toluene (85–90)[b]	8
3,4-Dimethoxybenzonitrile	*p*-Menthene	3,4-Dimethoxytoluene (85–90)	8
3,4,5-Trimethoxybenzonitrile	*p*-Menthene	3,4,5-Trimethoxytoluene (85–90)	8
3,4-Methylenedioxy-5-methoxybenzonitrile	*p*-Menthene	3,4-Methylenedioxy-5-methoxytoluene (85–90)	8
1-Cyanonaphthalene	*p*-Menthene	1-Methylnaphthalene (85–90)	8
2-Cyanonaphthalene	*p*-Menthene	2-Methylnaphthalene (85–90)	8
9-Cyanophenanthrene	*p*-Menthene	9-Methylphenanthrene (85–90)	8
Benzylnitrile	*p*-Menthene	Ethylbenzene (70–80)	8
$PhCH_2CH_2CH_2CHPhCN$	*p*-Menthene	$PhCH_2CH_2CH_2CHPhCH_3$ (70–80)	8
Tridecanonitrile	*p*-Menthene + H_2	Tridecane (58), tritridecylamine (8)	45
Tetradecanonitrile	*p*-Menthene + H_2	Tetradecane (53), tritetradecylamine (12)	45
Pentadecanitrile	*p*-Menthene + H_2	Pentadecane (41), tripentadecylamine (21)	45
Hexadecanitrile	*p*-Menthene + H_2	Hexadecane (44), trihexadecylamine (26)	45
Octadecanitrile	*p*-Menthene + H_2	Octadecane (35), trioctadecylamine (20)	45
2-Cyanopyridine	*p*-Menthene	2-Methylpyridine (85–90)	8
3-Cyanopyridine	*p*-Menthene	3-Methylpyridine (85–90)	8
4-Cyanopyridine	*p*-Menthene	4-Methylpyridine (85–90)	8
3-Pyridylacetonitrile	*p*-Menthene	3-Ethylpyridine (85–90)	8
4-Cyanoquinoline	*p*-Menthene	4-Methylquinoline (85–90)	8
6-Methoxy-4-cyanoquinoline	*p*-Menthene	6-Methoxy-4-methylquinoline (85–90)	8

[a] See also α,β-unsaturated nitriles in Table IX. [b] Concurrent hydrogenolysis of halide.

TABLE XIII. Catalytic Transfer Reduction of C=N Compounds (Pd/C Catalyst)

Acceptor	Donor	Product (yield)	Ref
PhCH=NPh	Cyclohexene	$PhNH_2$ (44)	42
$PhCH{=}NCH_2CH_2Ph$	Tetralin	CH_3CH_2Ph, CH_3Ph (?)	43
$PhCH_2CH{=}NCH_2CH_2Ph$	Tetralin	CH_3CH_2Ph (60)	43
$(Ph)_2C{=}NOH$	Cyclohexene	$PhCH_2Ph$ (75)	33
$PhCO(Ph)C{=}NNHPh$	Cyclohexene	$PhCOCH_2Ph$ (78)	33
$PhCH_2(Ph)C{=}NOH$	Cyclohexene	$PhCH_2CH_2Ph$ (40)	33
$PhCH_2(Ph)C{=}NNHPh$	Cyclohexene	$PhCH_2CH_2Ph$ (45)	33

nitro group is reduced,[48] whereas regular catalytic hydrogenation proceeds to give the fully reduced polyamines.



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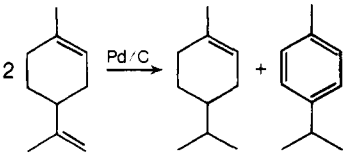
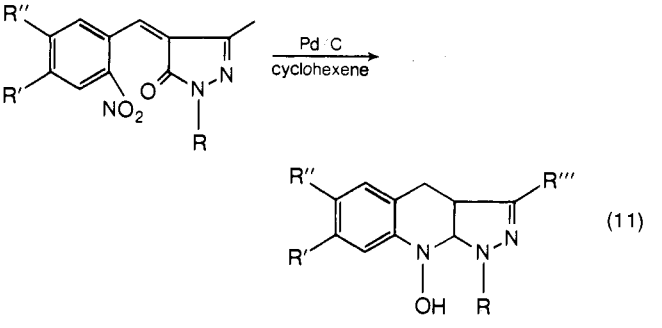


(10)

D. Special Synthetic Applications

In this section we point out some particularly interesting or useful applications of catalytic transfer hydrogenation. This process has been used, for instance, for the synthesis of heterocyclic compounds from the appropriate nitro compounds, as shown in eq 11.[27]



(11)

The tendency of amines to transfer hydrogen has also been used in the syntheses of piperidine and pyrrolidine (eq 12 and 13). The same reaction can also be used,

$$NH_2(CH_2)_5NH_2 \xrightarrow{\text{Raney nickel}} 80\%\ \text{piperidine} + NH_3 \qquad (12)$$

$$NH_2(CH_2)_4NH_2 \xrightarrow{\text{Raney nickel}} 80\%\ \text{pyrrolidine} + NH_3 \qquad (13)$$

under the appropriate conditions, to synthesize secondary amines according to eq 14.[49] The mechanism is probably

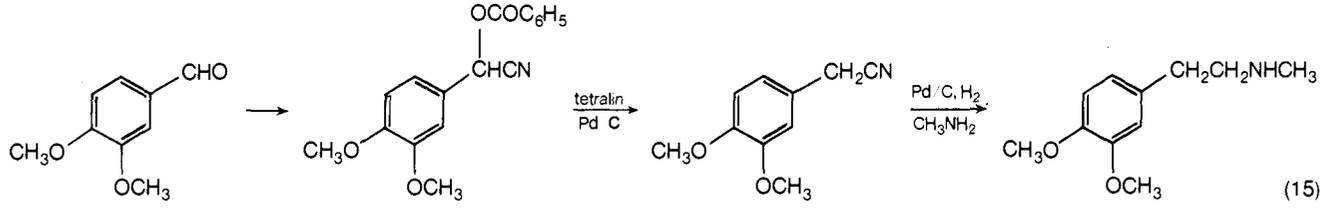
$$2RCH_2NH_2 \xrightarrow[70\text{–}90\%]{\text{Raney nickel}} (RCH_2)_2NH + NH_3 \qquad (14)$$

similar to that invoked for the side reaction leading to trialkylamines during the hydrogenolysis of nitriles (section III.B.1. Initially a hydrogen abstraction to the intermediate imine must occur, however.[50]

The hydrogenolysis of nitriles in the presence of amines can give excellent yields of pharmacologically active amines. The synthesis of epinin dimethyl ether is given in eq 15.[60]

TABLE XIV. Catalytic Transfer Hydrogenation of Nitro Compounds (Pd/C Catalyst)

Acceptor	Donor	Product (Yield, %)	Ref
Nitropropane	Cyclohexene	*n*-Propylamine (55)	48
Nitrobenzene	Cyclohexene	Aniline (93)	48
o-Nitrotoluene	Cyclohexene	o-Toluidine (100)	48
	α-Phellandrene	o-Toluidine (55)	38
m-Nitrotoluene	Cyclohexene	*m*-Toluidine (65)	48
p-Nitrotoluene	Cyclohexene	*p*-Toluidine (95)	48
	α-Phellandrene	*p*-Toluidine (90)	38
4-Nitro-*m*-xylene	Cyclohexene	4-Amino-*m*-xylene (86)	48
2-Nitro-*m*-xylene	Cyclohexene	2-Amino-*m*-xylene (10)	48
2-Nitro-*p*-xylene	Cyclohexene	2-Amino-p-xylene (67)	48
p-*tert*-Butylnitrobenzene	Cyclohexene	*p*-*tert*-Butylaniline (54)	48
1-Nitronaphthalene	Cyclohexene	1-Aminonaphthalene (71)	48
	α-Phellandrene	1-Aminonaphthalene (95)	38
o-Nitrophenol	Cyclohexene	o-Aminophenol (88)	48
p-Nitrophenol	Cyclohexene	*p*-Aminophenol (51)	48
2-Nitroresorcinol	Cyclohexene	2-Aminoresorcinol (17)	48
p-Nitroanisole	Cyclohexene	*p*-Anisidine (83)	48
2,5-Diethoxynitrobenzene	Cyclohexene	2,5-Diethoxyaniline (96)	48
o-Nitrobenzaldehyde	Cyclohexene	o-Aminobenzaldehyde (10)	48
m-Nitrobenzaldehyde	Cyclohexene	*m*-Aminobenzaldehyde (10)	48
p-Nitrobenzaldehyde	Cyclohexene	*p*-Aminobenzaldehyde (10)	48
o-Nitroacetophenone	Cyclohexene	o-Aminoacetophenone (89)	48
m-Nitroacetophenone	Cyclohexene	*m*-Aminoacetophenone (75)	48
p-Nitroacetophenone	Cyclohexene	*p*-Aminoacetophenone (98)	48
1-Nitroanthraquinone	Cyclohexene	o-Aminoanthraquinone (58)	48
o-Nitrobenzoic acid	Cyclohexene	o-Aminobenzoic acid (92)	48
m-Nitrobenzoic acid	Cyclohexene	*m*-Aminobenzoic acid (58)	48
p-Nitrobenzoic acid	Cyclohexene	*p*-Aminobenzoic acid (96)	48
o-Nitrobenzonitrile	Cyclohexene	o-Aminobenzonitrile (59)	48
m-Nitrobenzonitrile	Cyclohexene	*m*-Aminobenzonitrile (87)	48
o-Nitroaniline	Cyclohexene	o-Phenylenediamine (0)	48
m-Nitroaniline	Cyclohexene	*m*-Phenylenediamine (0)	48
p-Nitroaniline	Cyclohexene	*p*-Phenylenediamine (0)	48
o-Nitroacetanilide	Cyclohexene	o-Aminoacetanilide (100)	48
m-Nitroacetanilide	Cyclohexene	*m*-Aminoacetanilide (81)	48
p-Nitroacetanilide	Cyclohexene	*p*-Aminoacetanilide (27)	48
N,*N*-Dimethyl-*m*-nitroaniline	Cyclohexene	*N*,*N*-Dimethyl-*m*-phenylenediamine (73)	48
2-Nitrothiophene	Cyclohexene	2-Aminothiophene (0)	48
o-Dinitrobenzene	Cyclohexene	o-Nitroaniline (2)	48
m-Dinitrobenzene	Cyclohexene	*m*-Nitroaniline (80)	48
	α-Phellandrene	*m*-Nitroaniline (85)	38
p-Dinitrobenzene	Cyclohexene	*p*-Nitroaniline (2)	48
2,4-Dinitrotoluene	Cyclohexene	2,4-Diaminotoluene (75)	48
2,4-Dinitro-*tert*-butylbenzene	Cyclohexene	2,4-Diamino-*tert*-butylbenzene (95)	48
1,8-Dinitronaphthalene	Cyclohexene	1,8-Diaminonaphthalene (97)	48
2,4-Dinitrophenol	Cyclohexene	2,4-Diaminophenol (65)	48
3,5-Dinitrobenzoic acid	Cyclohexene	3-Amino-5-nitrobenzoic acid (60)	48
Picric acid	Cyclohexene	Picramic acid (28)	48
1,3,5-Trinitrobenzene	Cyclohexene	3,5-Dinitroaniline (9)	48
3-Nitro-*N*-methyl-2-pyridone	Cyclohexene	3-Amino-*N*-methyl-2-pyridone (90)	36
3-Nitro-*N*-methyl-4-pyridone	Cyclohexene	3-Amino-*N*-methyl-4-pyridone (100)	36



(15)

Catalytic transfer hydrogenolysis has been used in the synthesis of branched polyphenyls (eq 16). Finally selected cleavage of a chromenone was possible *via* a transfer reduction (eq 17).[35] These are some of the more unusual applications of this reaction.

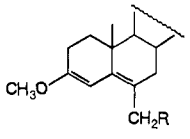
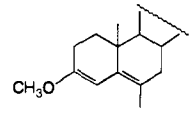
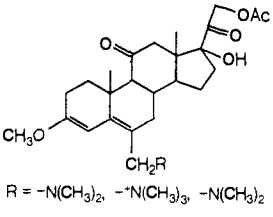
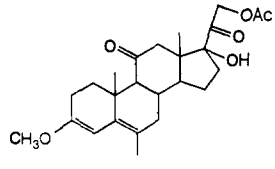
IV. Mechanism

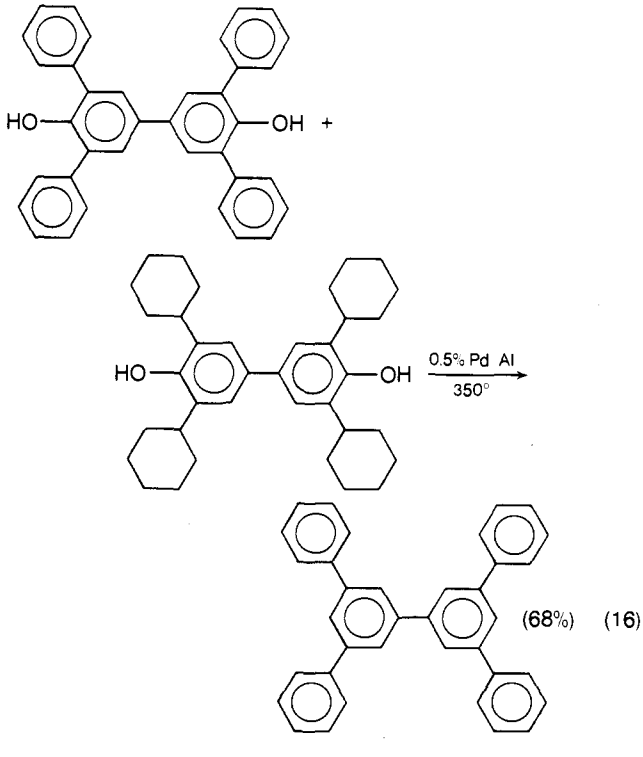
It should be understood at the outset that catalytic transfer hydrogenation is not simply regular catalytic hydrogenation with organic compounds as an alternative

TABLE XV. Catalytic Transfer Hydrogenolysis of Halides (Pd/C Catalyst)

Compound	Donor	Product (yield, %)	Ref
p-Fluorobenzoic acid	Limonene	Benzoic acid (0)	14
p-Chlorobenzoic acid	Limonene	Benzoic acid (90)	14
o-Chlorobenzoic acid	Limonene	Benzoic acid (90)	14
o-Bromobenzoic acid	Limonene	Benzoic acid (90)	14
p-Chlorocinnamic acid	Limonene	Hydrocinnamic acid (9)	14
3-ClPhCH=CHCOOCH$_3$	Limonene	PhCH$_2$CH$_2$COOCH$_3$ (90)	14
4-ClPhCH=CHCOPh	α-Phellandrene	PhCH$_2$CH$_2$COPh (90)	14
o-Chlorobenzonitrile	*p*-Menthene	Toluene (85–90)	8
p-Chlorobenzonitrile	*p*-Menthene	Toluene (85–90)	8
Benzoyl chloride	Cyclohexene	Benzaldehyde (10)	42

TABLE XVI. Catalytic Transfer Hydrogenolysis of Benzylic and Allylic Compounds

Compound	Catalyst	Donor	Product (yield, %)	Ref
Benzyl chloride	Pd/C	Cyclohexene	Toluene (50)	42
Cinnamyl chloride	Pd/C	Cyclohexene	*n*-Propylbenzene (50)	42
Benzylamine	Pd/C	Tetralin	Toluene (85)	43
Tribenzylamine	Pd/C	Tetralin	Toluene (74)	43
PhCH$_2$NHCH$_2$CH$_2$Ph	Pd/C	Tetralin	Toluene + ethylbenzene (?)	43
3,4-(CH$_3$)$_2$OPhCH(OCOPh)CN	Pd/C	Tetralin	3,4-(CH$_3$O)$_2$PhCH$_2$CN (70)	58
4-CH$_3$OPhCH(OCOPh)CN	Pd/C	Tetralin	4-CH$_3$OPhCH$_2$CN (70)	58
3,4-Dioxymethylene-PhCH(OCOPh)CN	Pd/C	Tetralin	3,4-Dioxymethylene-PhCH$_2$CN (70)	58
 (20 dif. steroids)	Pd/C	Cyclohexene	 (?)	28
 R = $-N(CH_3)_2$, $-{}^{+}N(CH_3)_3$, $-N(CH_3)_2$	Raney nickel	Methanol pH 7–7.5	 (75)	28
17α-Acetoxy-6-hydroxymethyl-3-methoxy-androstane-3,5-dien-20-one	Pd/C	Cyclohexene	17α-Acetoxy-6-methyl-3-methoxy-androstane-3,5-dien-20-one (?)	29
Benzoin	Raney nickel	Cyclohexanol	Bibenzyl (58)	40



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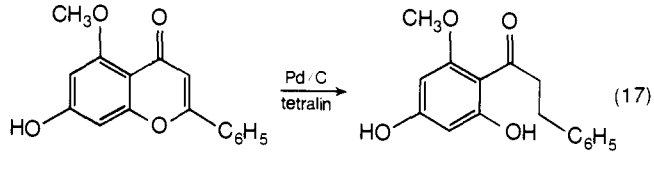


(17)

source of hydrogen. Therefore, some interest is attached to mechanistic considerations for this reaction although the reported experimental evidence is sparse.

Evidence for the view that a somewhat different reaction is at hand is contained in the following observations. Platinum black, or rhodium/carbon, which is normally quite an active catalyst for the reduction of double bonds for instance, fails to reduce such linkages under the standard conditions with active donors. Palladium is active under the same conditions.[14] Furthermore, compounds such as *p*-menthane and decalin, which release hydrogen at 144° (xylene as solvent), fail to hydrogenate cinnamic acid even after 16 hr with palladium as catalyst. This indicates that the mere presence of gaseous hydrogen is not adequate to give hydrogenation. It also shows that palladium plays an exceptional role in these reactions as previously mentioned.

Few mechanistic studies of catalytic transfer hydrogenation have been reported. In addition to the experimental variables discussed in section II, some studies have

been made on the inhibition of the disproportionation of cyclohexene in the presence of various acceptors.[32] Other work, to be discussed later, has specifically focused on the disproportionation of cyclohexene. One must therefore turn to some results from catalytic hydrogenation with gaseous hydrogen in order to permit a meaningful discussion of mechanisms at this point.

An early mechanistic proposal is that of Wieland.[5] He suggested that the donor reacted initially with the palladium catalyst to form a palladium hydride intermediate which then added to the acceptor, as in eq 18 and 19, and then decomposed.

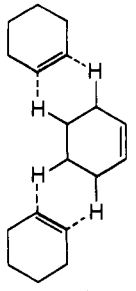
$$DH_2 + Pd \longrightarrow PdH_2 + D \qquad (18)$$

$$R_2C{=}CR_2 + PdH_2 \longrightarrow R_2C(HPd)-CR_2(H) \longrightarrow R_2C(H)-CR_2(H) + Pd \qquad (19)$$

The postulated palladium hydride was never isolated, but it was believed that the considerable reduction in vapor pressure of alcohols when mixed with colloidal palladium could be explained by possible organopalladium intermediates, possibly of type **1** or **2**, in eq 20.

$$R_2C(H)-O-H + Pd \longrightarrow \underset{\mathbf{1}}{R_2C(Pd-H)-O-H} \text{ or } \underset{\mathbf{2}}{R_2C(H)-O-Pd-H} \qquad (20)$$

Braude, *et al.*,[32] prefer a concerted mechanism, wherein donor and acceptor, or in the case of disproportionation, another unit of donor, are coadsorbed on the catalyst and effect hydrogen transfer directly. Since they could not detect cyclohexadiene as an intermediate, when examining the disproportionation of cyclohexene, they proposed a termolecular mechanism, possibly including hydrogen bridging, as shown (**3** and **4**). It has



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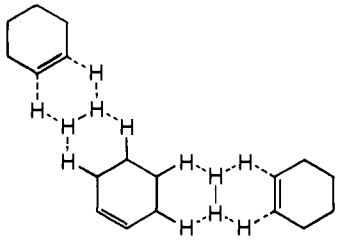
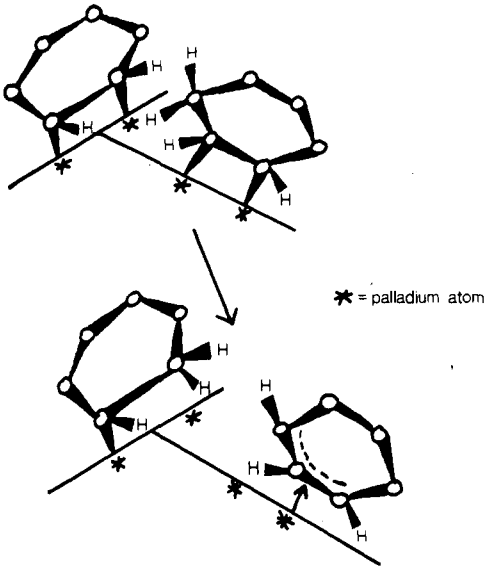


4

been noted that some hydrogen is necessary before disproportionation can take place.[17,32] More recent studies have, however, presented evidence for a cyclohexadiene intermediate and have also shown that the observed kinetics with palladium fit a second-order reaction best. Studies of the specific activity of the catalyst have further shown an interesting phase behavior, with maxima occurring with 4, 10–11, and 20 palladium atoms per intermediate complex.[60] The suggested model is shown as **5.**

A systematic analysis of catalytic transfer hydrogenation and hydrogenolysis must account for several processes including the dehydrogenation of the donor, the rearrangement or disproportionation of the donor, the stereochemistry of the hydrogen transfer, and any eventual transformation of the product acceptor while still under the influence of the catalyst. As was noted above, actual experimental studies directed toward the determination of this mechanism are very limited and refer mostly to the disproportionation of cyclohexene. We must therefore turn to a consideration of normal catalytic hydrogenation for possible mechanistic clues.



5, proposed model for transfer of one allylic hydrogen

For this purpose we have the general mechanistic proposal of Horiuti and Polyani[61] for catalytic hydrogenation which is shown in eq 21–24.

$$H_2 + 2\S \rightleftharpoons 2H(\S) \qquad (21)$$

§ = catalyst

$$R_2C{=}CR_2 + 2\S \rightleftharpoons R_2C(\S)-CR_2(\S) \qquad (22)$$

$$R_2C(\S)-CR_2(\S) + H(\S) \rightleftharpoons R_2C(\S)-CR_2(H) + 2\S \qquad (23)$$

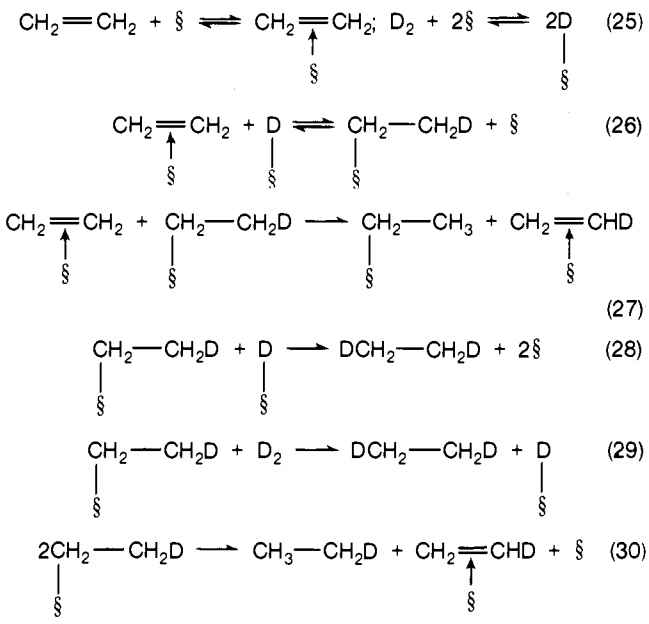
$$R_2C(\S)-CR_2(\S) + H(\S) \longrightarrow R_2C(H)-CR_2(H) + 2\S \qquad (24)$$

What is here suggested then is the activation/adsorption of both hydrogen and acceptor in a reversible process, followed by stepwise cis addition of the activated hydrogen. Details on the nature of the adsorbed/activated species are not provided.

Bond, *et al.*, have determined the applicability of such a mechanism to the addition of deuterium to ethylene over Pd/Al_2O_3 at $-16°$. Their proposed mechanism is shown in eq 25–30.[62]

The additional steps were necessary to account for the overall incorporation of deuterium to give an empirical formula of $C_2H_{2.63}D_{1.37}$. No details are available on the nature of the intermediates. An important addition to the Polyani mechanism is the inclusion of the hydrogen transfer step (eq 27) and the disproportionation (eq 30).

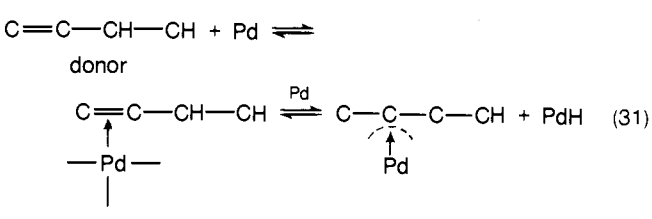
Suitable modifications of these proposals could certainly account for many of the results found in catalytic transfer hydrogenation. In order to further the interpretation of these results, it would seem desirable to consider these reactions not in terms of vague associations of catalyst and organic molecules, but in terms of the known chemistry of palladium which includes the formation of σ



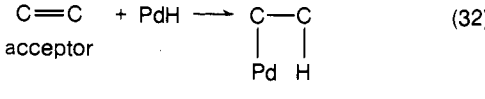
and π bonds, as well as the formation of σ and π complexes.[63]

In the case of palladium, and for that matter nickel, it should be noted that the corresponding hydrides of the approximate composition $PdH_{0.6-0.7}$ and $NiH_{0.7-0.8}$ exist and can be formed under mild conditions from the metals and hydrogen gas.[64,65] The suggested structure for the palladium hydride, based on X-ray analysis, is an alternate layering of Pd and PdH units. The nickel hydride is relatively unstable. It is therefore not at all unreasonable to invoke hydride intermediates as Wieland first suggested.

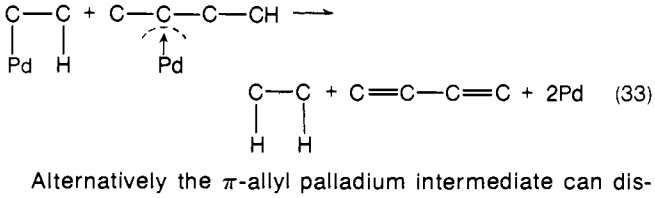
The proposed first step is the formation of a π complex between the surface atoms of the palladium catalyst and subsequent rearrangement to a π-allyl complex with the formation of palladium hydride, as in eq 31.



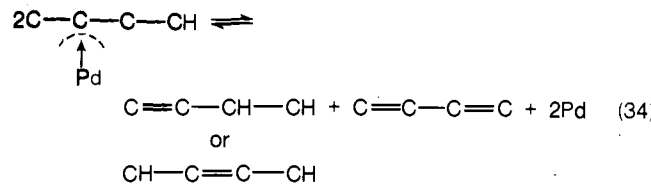
In a second step the palladium hydride (still considered a part of the catalyst and not in solution, of course) adds to the acceptor as in eq 32. This is followed by a bi-



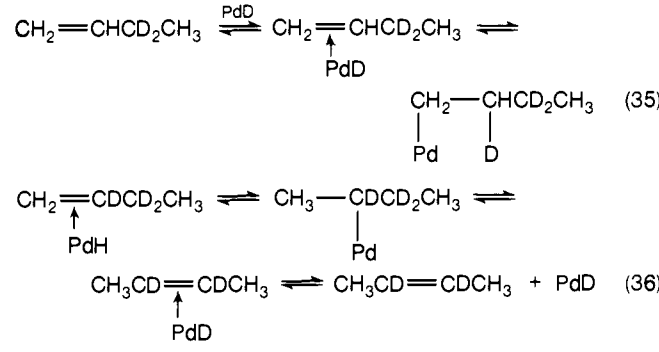
molecular reaction of the hydride with a donor-palladium π-allyl complex to give the reduced acceptor and the dehydrogenated donor (eq 33).



Alternatively the π-allyl palladium intermediate can disproportionate with itself, as in eq 34, giving back either the original or isomerized donor plus dehydrogenated donor. This scheme is essentially an adaptation of mech-

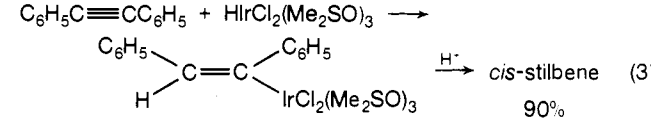


anisms which have been proposed to account for the isomerization of olefins under the influence of palladium catalysts,[66-69] all of which have in common the intermediacy of palladium hydride, π-complexed and σ-bonded palladium, and equilibration between these two forms, such as the mechanism suggested for the scrambling of deuterium label in 3,3-dideuteriobutene-1[67] (eq 35 and 36).

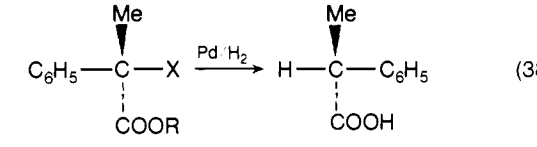


In our proposed mechanism, it is especially in eq 33 that the stereochemical requirements of the donor could play an important role. The inhibition of disproportionation of cyclohexene by certain acceptors such as benzaldehyde[42] may be due to a preferential complexation of the acceptor, as in eq 31.

The stereochemical aspects of catalytic hydrogenation have been reviewed.[70] It is the newer results from homogeneous hydrogenation, however, which substantiate at least one aspect of hydrogenation, namely the cis addition of hydride intermediates. Thus the homogeneous hydrogenation catalyst $HIrCl_2(Me_2SO)_3$, formed from $IrCl_3(Me_2CO)_3$ in the presence of alcohols, adds cis to tolan. At low temperatures the intermediate can be isolated and has the structure shown in eq 37.[56] Whether similar complexes can be isolated with palladium remains to be seen.



The second stereochemical aspect, namely the stereochemistry of reduction at a saturated Pd-C bond (hydrogenolysis), has been explored with optically active benzylic halides as shown in eq 38. The reaction is highly



stereospecific and leads to inversion.[71] Intermediate formation of a Pd-C bond (with retention) is proposed. So far no results are available for catalytic transfer hydrogenation.

We may summarize the mechanistic considerations by stating that little work has been done in this area, and that those results which are available are not inconsistent

with mechanisms proposed for regular catalytic hydrogenation. Of particular interest, however, is the role of the donor in such reactions, and this remains to be explored.

V. Summary and Prospects

We have endeavored to show that an interesting alternative to conventional catalytic hydrogenation exists in catalytic transfer hydrogenation with an organic molecule as hydrogen donor. This reaction, using predominantly palladium, but occasionally also Raney nickel, or soluble transition metal catalysts, permits the reduction of a wide variety of olefins, nitriles, nitro compounds, and other nitrogen-containing unsaturated functional groups, as well as hydrogenolysis of benzylic and allylic functional groups and the replacement of aromatic halogen. The donors are readily available organic compounds such as cyclohexene and alcohols. The yields are in most cases excellent and fully comparable to those of normal catalytic hydrogenation. The reaction is somewhat more selective than regular hydrogenation and in special cases, such as the reduction of polyunsaturated steroids, has proven superior (section III.C).

There is *no* question as to the greater experimental convenience with catalytic transfer hydrogenation, most reactions being complete after 1 or 2 hr at reflux, without the use of elaborate apparatus. It is surprising that routine use is not made of this process. The dehydrogenated donors, such as benzene or naphthalene, cause no more problems than the usual removal of an inert solvent.

Prospects for future work include the development of a catalyst–donor system capable of reducing carbonyl functions under mild conditions, wider studies on the applicability of this reaction, and the establishment of the mechanism.

Early workers such as Wieland,[5] thinking within a broader frame of reference, investigated these reactions as models for biological reductions. This idea well deserves to be revived, because the donor–catalyst–acceptor model used in these reactions does indeed have some remarkable similarities to an enzyme system. It appears that adsorption of both donor and acceptor in a stereochemically favorable relationship is necessary for reduction, for instance.[48] There is competitive inhibition of the catalyst, as shown by the adsorption, but nonreduction of carbonyl compounds.[48] The reductions are generally stereospecific. The only major difference, in fact, is the slower rate, which could be an asset to experimental investigation.

We hope to have demonstrated that catalytic transfer hydrogenation is worthy of greater attention.

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VI. References

(1) E. A. Braude and R. P. Linstead, *J. Chem. Soc.*, 3544 (1954).
(2) A. Furst, R. C. Berlo, and S. Hooton, *Chem. Rev.*, **65**, 51 (1965).
(3) E. A. Braude, R. P. Linstead, L. M. Jackman, P. W. D. Mitchell, and K. R. H. Wooldridge, *Nature (London)*, **169**, 100 (1952).
(4) E. Knoevenagel and B. Bergdolt, *Chem. Ber.*, **36**, 2857 (1903).
(5) H. Wieland, *Chem. Ber.*, **45**, 484 (1912).
(6) G. S. Pavlov and N. D. Zelinski, *Chem. Ber.*, **66**, 1420 (1933).
(7) B. B. Corson and V. N. Ipatieff, *J. Amer. Chem. Soc.*, **61**, 1056 (1939).
(8) K. Kindler and K. Lührs, *Chem. Ber.*, **99**, 227 (1966).
(9) J. C. Bailar, Jr., and H. Hatani, *J. Amer. Chem. Soc.*, **89**, 1592 (1967).
(10) M. Gullotti, R. Ugo, and S. Colonna, *J. Chem. Soc. C*, 2652 (1971).
(11) J. Trocha-Grimshaw and H. B. Henbest, *Chem. Commun.*, 544 (1967).
(12) Y. Sasson and J. Blum, *Tetrahedron Lett.*, 2167 (1971).
(13) M. E. Volpin, V. P. Kukolev, V. O. Chernyshev, and I. S. Kolomnikov, *Tetrahedron Lett.*, 4435 (1971).
(14) K. Kindler and K. Lührs, *Justus Liebigs Ann. Chem.*, **685**, 36 (1965).
(15) R. P. Linstead, A. F. Millidge, S. L. S. Thomas, and A. L. Walpole, *J. Chem. Soc.*, 1146 (1937).
(16) R. P. Linstead, K. O. A. Michaelis, and S. L. S. Thomas, *J. Chem. Soc.*, 1139 (1940).
(17) S. Siegel and G. V. Smith, *J. Amer. Chem. Soc.*, **82**, 6087 (1960).
(18) A. S. Hussey, T. A. Schenach, and R. H. Baker, *J. Org. Chem.*, **33**, 3258 (1968).
(19) S. Akabori and K. Saito, *Chem. Ber.*, **63**, 2245 (1930).
(20) R. C. Elderfield and A. Maggiolo, *J. Amer. Chem. Soc.*, 71, 1906 (1949).
(21) W. Doering and S. J. Rhoads, *J. Amer. Chem. Soc.*, **75**, 4738 (1953).
(22) J. Heer and K. Miescher, *Helv. Chim. Acta*, **31**, 1289 (1948).
(23) H. Atkins, L. M. Richards, and J. W. Davis, *J. Amer. Chem. Soc.*, **63**, 1320 (1941).
(24) R. P. Linstead and S. L. S. Thomas, *J. Chem. Soc.*, 1127 (1940).
(25) A. Giaffe and R. Pallaud, *C. R. Acad. Sci.*, **259**, 4722 (1964).
(26) A. Giaffe and A. Plotiau, *C. R. Acad. Sci.*, **261**, 164 (1965).
(27) R. T. Coutts and J. B. Edwards, *Can. J. Chem.*, **44**, 2009 (1966).
(28) D. Burn, G. Cooley, M. T. Davies, A. K. Hiscock, D. N. Kirk, V. Petrov, and D. M. Williamson, *Tetrahedron*, **21**, 569 (1965).
(29) D. Burn, D. N. Kirk, and V. Petrov, *Tetrahedron*, **21**, 1619 (1965).
(30) H. E. Eschinazi and E. D. Bergmann, *J. Amer. Chem. Soc.*, **72**, 5651 (1950).
(31) A. Gaiffe and A. Plotiau, *C. R. Acad. Sci.*, **263**, 891 (1966).
(32) E. A. Braude, R. P. Linstead, and P. W. D. Mitchell, *J. Chem. Soc.*, 3578 (1954).
(33) D. R. Moore and E. W. Robb, *Chem. Ind. (London)*, 441 (1967).
(34) P. Scribe and R. Pallaud, *C. R. Acad. Sci.*, **256**, 1120 (1963).
(35) D. Pillon, *Bull. Soc. Chim. Fr.*, **5**, 39 (1965).
(36) Y. Ahmad and D. H. Hey, *J. Chem. Soc.*, 4516 (1954).
(37) A. Gaiffe and A. Plotiau, *C. R. Acad. Sci.*, **261**, 164 (1965).
(38) R. Pallaud and A. Huynh, *C. R. Acad. Sci.*, **252**, 2896 (1961).
(39) M. Orchin, *J. Amer. Chem. Soc.*, **66**, 535 (1944).
(40) E. C. Kleiderer and E. C. Kornfeld, *J. Org. Chem.*, **13**, 455 (1948).
(41) A. S. Hay, *Tetrahedron Lett.*, **20**, 1577 (1969).
(42) E. A. Braude, R. P. Linstead, K. R. H. Wooldridge, and P. W. D. Mitchell, *J. Chem. Soc.*, 3595 (1954).
(43) K. Kindler and W. Peschke, *Justus Liebigs Ann. Chem.*, **497**, 193 (1932).
(44) K. Kindler and W. Peschke, *Justus Liebigs Ann. Chem.*, **501**, 191 (1933).
(45) K. Kindler and K. Lührs, *Justus Liebigs Ann. Chem.*, **707**, 26 (1967).
(46) K. Kindler and K. Lührs, *Chem. Ber.*, **99**, 227 (1966).
(47) W. Cocker, P. V. R. Shannon, and P. A. Staniland, *J. Chem. Soc. C*, 41 (1966).
(48) E. A. Braude, R. P. Linstead, and K. R. H. Wooldridge, *J. Chem. Soc.*, 3586 (1954).
(49) K. Kindler, G. Melamed, and D. Matthies, *Justus Liebigs Ann. Chem.*, **644**, 23 (1961).
(50) K. Kindler and D. Matthies, *Chem. Ber.*, **95**, 1992 (1962).
(51) K. Kindler and D. Matthies, *Chem. Ber.*, **96**, 924 (1963).
(52) R. Mozingo, D. E. Wolf, S. A. Harris, and K. Folkers, *J. Amer. Chem. Soc.*, **65**, 1013 (1943).
(53) W. A. Bonner, *J. Amer. Chem. Soc.*, **74**, 1033 (1952).
(54) H. Atkins, D. Rae, J. W. Davis, G. Hager, and K. Hoyle, *J. Amer. Chem. Soc.*, **70**, 381 (1948).
(55) R. P. Linstead and K. O. A. Michaelis, *J. Chem. Soc.*, 1134 (1940).
(56) J. Trocha-Grimshaw and H. B. Henbest, *Chem. Commun.*, 757 (1968).
(57) T. J. Nestrick, M.S. Thesis, Oakland University, Rochester, Mich., 1972.
(58) K. Kindler and W. Peschke, *Arch. Pharm.*, 431 (1933).
(59) K. Kindler and F. Hesse, *Arch. Pharm.*, 439 (1933).
(60) S. Carra and V. Ragaini, *Tetrahedron Lett.*, 1079 (1967).
(61) I. Horiuti and M. Polyani, *Trans. Faraday Soc.*, **30**, 1164 (1934).
(62) G. C. Bond, J. J. Phillipson, P. B. Wells, and J. M. Winterbottom, *Trans. Faraday Soc.*, **62**, 443 (1966).
(63) P. M. Maitlis, "The Organic Chemistry of Palladium," Vol. I and II, Academic Press, New York, N. Y., 1971.
(64) B. Siegel and G. G. Libowitz in "Metal Hydrides" W. M. Mueller, J. P. Blackledge, and G. G. Libowitz, Ed., Academic Press, New York, N. Y., 1968, p 634 ff.
(65) Reference 64, p 637.
(66) J. F. Harrod and A. J. Chalk, *Nature (London)*, **205**, 280 (1965).
(67) R. Cramer and R. V. Lindsay, Jr., *J. Amer. Chem. Soc.*, **88**, 3534 (1966).
(68) N. R. Davies, *Rev. Pure Appl. Chem.*, 17, 83 (1967).
(69) G. V. Smith and J. R. Swoap, *J. Org. Chem.*, **31**, 3904 (1966).
(70) R. L. Burwell, Jr., *Chem. Rev.*, **57**, 895 (1957).
(71) A. M. Khan, F. J. McQuillin, and I. Jardine, *J. Chem. Soc. C*, 136 (1967).